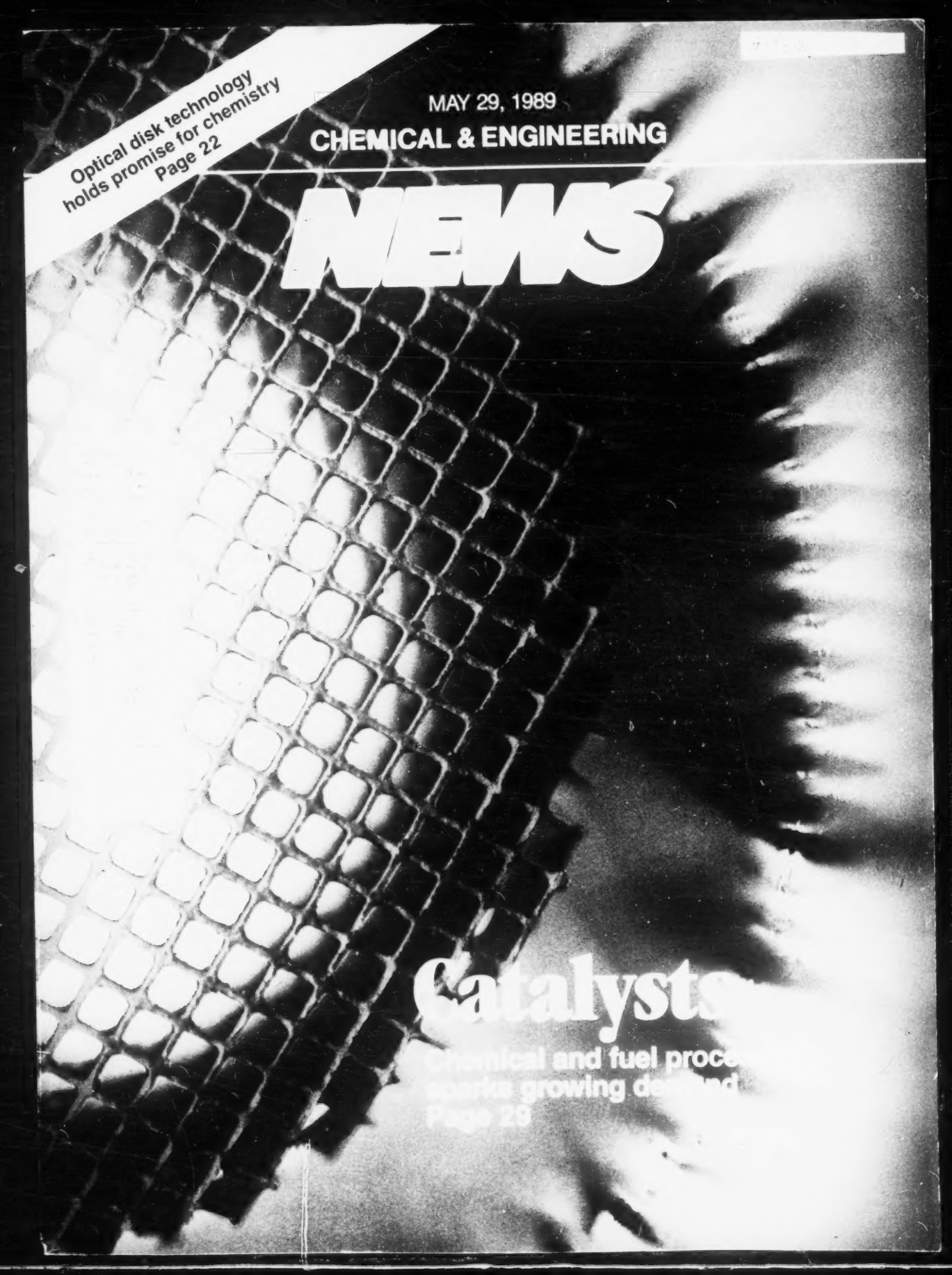
MAY 29, 1989

CHEMICAL & ENGINEERING

NEWS

Optical disk technology holds promise for chemistry
Page 22



Catalysts

Chemical and fuel proce
markets growing de
Page 29

CHEMICAL & ENGINEERING NEWS

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MAY 29, 1989

News of the Week

■ **Industry and government efforts to deal with Alaska oil spill called slow, inadequate, and confused in report to President Bush.** Page 4

■ **Scientists at National Institutes of Health carry out first test using genetically altered cells in a human patient.** Page 5

■ **Higher pay for patent, FDA examiners urged by the Pharmaceutical Manufacturers Association.** Page 5

■ **Representatives of chemical industry air views on chemical weapons issues.** Page 6

■ **Du Pont will purchase Howson-Algraphy, Britain's largest lithography plate firm, for $400 million.** Page 6

Business

PPG is expanding overseas, adding noncyclical products in ongoing program to buffer effects of U.S. business cycle; Shell tightens in on expansion plans for Far East; data show correlation between capacity use and inflation. **Page 9**

Insights

Du Pont chief Edgar S. Woolard Jr. sees need for chemical companies to develop an environmental stewardship in line with public desires and expectations. **Page 12**

Government

Review of Superfund will call for revamping its implementation, though former head of program believes no major changes are needed. **Page 17**

Science/Technology

Advances in optical disc technology and an expansion of the topics available on disc provide for a range of science, education uses; series of organotitanium reagents facilitate aldehyde additions; new exchange resin developed for plutonium recovery. **Page 22**

ACS News

A French-designed multimedia exhibit about chemistry acquired recently by the society will tour major science museums across the U.S. and Canada beginning next month. **Page 58**

Cover: Engelhard honeycomb catalytic system designed for automotive engines

Letters 2

Concentrates
Business 7
Government 16
Science/Technology 21

The Departments
Software/Database Update 28
New Products 46
People 61
Newscripts 76

Product Report

Catalysts find growing use in making chemicals and polymers, fuels from petroleum, products that reduce pollution, and biological materials. Page 29

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LETTERS

Patent protection

SIR: This is in regard to your article, "Foreigners Win Almost Half of 1988 U.S. Patents" (C&EN, March 27, page 5). Counting the number of patents granted to foreigners in a given time period is a simple exercise. It is much more difficult to determine how much patent protection was awarded to applicants from different countries.

In the U.S., the first inventor gets the patent. In most other countries, patents are awarded to the first inventor to reach the patent office. In the U.S., we also have the benefit of a one-year grace period, which allows inventors to "swear behind" publications that appear prior to the filing of a patent application. This advantage is available in only one or two other countries. In most of the world, publication—no matter how briefly before filing—can cause a loss of patent rights.

These differences encourage U.S. inventors to take more time to perfect and broaden their inventions. The laws of other countries promote racing to reach the patent office as early as possible.

There is probably no practical way to compare the breadth of protection awarded to U.S. inventors as opposed to foreign inventors, but I suggest that U.S. inventors are perhaps not losing so much share in terms of real patent protection as the naked numbers of patents granted might seem to indicate. All patents are not equal!

R. C. Brown
Managing Patent Counsel
Union Carbide Corp.

Safety data sheets

SIR: I would like to comment on the letter from Mona F. Zady (C&EN, March 20, page 4) regarding material safety data sheets. I am the regulatory and technical coordinator for a major chemical company in California. In addition to all the federal Occupational Safety & Health Administration and Superfund regulations, we must contend with California's own OSHA, and the mammoth Safe Drinking Water & Toxic Enforcement Act of 1986 (known as Proposition 65). Our responsibility to our customers is tremendous, to the point where we employ a staff for management of our material safety data sheets.

In principle, I wholeheartedly agree with Zady's point that companies are exaggerating the potential hazards of some chemicals. I, personally, have been astounded when reviewing the toxicity information for "harmless" compounds such as sodium chloride, lactose, and potassium bicarbonate. I particularly agree with her point regarding the likelihood of user apathy developing when material safety data sheet warnings become out of hand, as in her sucrose citation. The real problem for me, however, is just the opposite: trying to effectively relay the legitimate hazards of chemicals worthy of concern. Although I am considerate of the liabilities potentially arising for my company should the required information fail to be included with hazardous items, I am much more worried about the casual and neophyte user (not to mention those for whom English is a second language!) who fails to take the time to read our data sheets or fails to adhere to the safety guidelines included therein.

Owing in large parts to the influence of Proposition 65 regarding carcinogenic chemicals, I would very much like to see the American National Standards Institute ratify a universally recognized symbol for carcinogens, as they have for flammable, corrosive, explosive, and toxic compounds. Many carcinogens are also suspect teratogens, making their impact not only immediate, but potentially present for generations. If asbestos set the tone for carcinogens of industrial concern, the list grows ever longer, and will only continue to do so as our empirical data accumulate.

Obviously, the safety gear recounted by Zady for handling sucrose is preposterous. But it is extremely important that the users of chemicals pay mindful attention to all warnings (on the label of the containers as well as on the data sheets). So many compounds have little or no toxicity data compiled on them, and for scores of others the information is outdated when you consider modern toxicological methods. When strident warnings are included, most of the time, they are there for a reason and are not discountable. The chemical industry mustn't allow its members to become cavalier about the inherent dangers of the field. The more we learn about chemical toxicology, the more overwhelming and frightening it becomes, Zady's observations notwithstanding.

Diana Hale Wilson
Gardena, Calif.

SIR: In her letter, Mona Zady commented on the safety equipment recommended in material safety data sheets for cleaning up spills of table sugar.

I think it should be pointed out that material safety data sheets are legal documents. Those of us who write, edit, and

Review To Call for Revamp of Superfund's Implementation

Despite heavy criticism from Congressional, environmental sources, former program head claims that there's no need for major changes

Lois R. Ember, C&EN Washington

Superfund was born in the turmoil of fear, and eight years later it is still embroiled in the flames of controversy. Not surprising for a difficult, costly, and complex program operating within a partisan, political framework.

Superfund, aimed at cleaning up abandoned hazardous waste sites, was conceived in the Carter Administration, which was generally supportive of environmental issues. But the bulk of its implementation fell to the Reagan Administration, which, according to one House aide, "was hostile to the whole program." The Reagan White House saw Superfund as a five-year program, and fought to ensure there would be no "son of Superfund."

That there will be a need for many sons of Superfund is now conceded by nearly everybody, including the former head of the program, J. Winston Porter. Porter also believes that the program, as he administered it, is on target.

However, many Congressional sources say the Bush Administration, recognizing that Superfund is in trouble, has undertaken a review to get the program back on track. The review is slated to be completed this week, on May 31, but that date is likely to slip to June 6.

The Reagan Administration's antagonism to Superfund led to a "bit of a bunker mentality," according to one critic, and the predictable

C&EN staff photos

Porter: got program to high level

results occurred. In the past two years more than a dozen reports have been published sharply critical of one or another aspect of the program. If there is a common theme to all the studies it is this: Superfund as reauthorized in 1986 is fine; its implementation is flawed, however.

Critics charge that the wellspring for this failed management was a lack of leadership at the political level at EPA. Says Sierra Club's Washington, D.C., representative A. Blakeman Early, the absence of leadership led to "many of the requirements in the law not being observed. EPA spent much of its time trying to get around the law, or interpreted the law at the margins of credibility."

Porter, who as a political appointee ran the program for three and a half years before he was asked to leave this March, disagrees. He believes that "The biggest problem with Superfund is the criticism that it is not working."

As he relates it, "EPA was usually on the defensive, always reacting to criticisms from Capitol Hill." There's a need for oversight, for independent review, Porter says, "especially for [a program] this big, expensive, and complicated, but I think it may have been overdone."

Given a second opportunity, Porter says, "I think I'd spend even more time and I would have my people spend more time explaining the program. We tried, but we were not very effective."

Many of the people contacted by C&EN lay the program's quagmire directly at Porter's feet, not just for his lack of communication but for what he communicated and for his method of implementing Superfund. These sources are quick to say that they believe Porter is a decent man who was doing what he thought best and what he thought the Administration wanted. But they strongly contend that he implemented the law as he interpreted it, not as Congress mandated it.

Porter conveyed the message that "he knew better than Congress how to clean up Superfund sites because he is an engineer and members of Congress are lawyers," a Senate staffer says. "After seeing him at many hearings I came away with the view that he knew how to do it, that he was the engineer, that he was smarter than others," says Sierra Club's Early. "His message: Let the experts make the decisions."

Porter is knowledgeable. He obtained a Ph.D. degree in chemical engineering from the University of California, Berkeley, and he is a registered professional engineer in California, Texas, and Virginia. He was chosen to run the Superfund program after Lee M. Thomas was elevated to EPA Administrator because Superfund is primarily an engineering and construction-centered law.

Former EPA official grades Superfund

J. Winston Porter was Environmental Protection Agency assistant administrator for Superfund in the final three and a half years of the second Reagan Administration. He divides Superfund into four parts and grades EPA's performance in each.

Screening: EPA has about 30,000 potential Superfund sites in its inventory. EPA and the states have done preliminary assessments at 27,000 of these sites. About 1200 sites at this point are actual Superfund sites. This whittling-down process is very valuable, and EPA and the states are doing about 2500 preliminary assessments a year. I give this part of the program at least an A−.

Emergency removal: This program corrects problems like leaking tanks. EPA spends about $100 million a year on this part. Close to 300 of these are done a year between EPA and responsible private parties. About 1800 have been done since the program started in 1981. This part of the program has functioned very well. I'd give it a solid A.

Enforcement and settlement: EPA and the Department of Justice have had about 500 settlements, meaning we reached agreement with potential responsible parties to either do an emergency removal or a long-term remedial cleanup. We've recovered over $1 billion, either in money recovered or agreements to do work. This part of the program is more complicated than the first two, but it has been improving. I'd give it a B or B+.

Remedial cleanups: This is the part of the program by which EPA and the states with their own contractors are doing the cleanup, paying for it out of Superfund money. This part of the program has the most room for improvement. I would give it about a C+ or B−, not because EPA is not working hard and not because it doesn't care. These are very tough problems technically. Many different views have to be considered. Every problem is different—no two sites are the same. Operating within the bureaucracy of the federal government is not easy.

But Superfund also operates in a political arena, demanding that the person who runs the program be a skilled diplomat and negotiator.

At EPA Porter says he worked very hard at "getting [staff] to think like project managers, engineers, and construction people," a task made difficult because EPA is "not an implementing agency." And he struggled to get responsible private parties not only to pay for cleanups but also to actually do them. "Three years ago, about 20% of the work was being done by responsible parties," he says. "When I left, about 50% of the work was being done by them."

Given the enormity of the cleanup task and the relatively limited funds available to carry it out, Porter's bent was to contain contamination at a lot of sites. Containment techniques are generally less costly and quicker to carry out than such permanent treatments as incineration. A Senate aide says Porter "tried very hard to nip permanent treatment in the bud. It is known that he went to Thomas and complained that one EPA regional office was using incineration too often. He believes that incineration is too expensive. I was told by high-level staff at EPA that this sent a chill throughout the program."

Porter tells C&EN that "The emphasis on treatment and its being equated to permanency is troublesome to me. I want a good remedy and that may not be treatment." Porter's way of addressing hazardous waste cleanup may be more correct from an engineering and economic point of view. But Congress said that its preference is to use permanent remedies and that it wants to attack as many sites as possible through permanent treatment.

This yawning chasm between Porter's implementation and Congress' mandate occurred because a fundamental issue has yet to be addressed by Congress, EPA, the states, and environmental groups, explains Gene A. Lucero, a partner in the Washington law firm Sidley & Austin and formerly director of EPA's Office of Waste Programs Enforcement. With only $8.1 billion to spend over five years and with cleanups averaging much more than $500,000 per site, choices have to be made.

"Is it better to deal with 1000 sites preliminarily [but with removal of the health risk] or should EPA really focus on permanent remedies at a few sites?" Lucero asks. Until this basic dialogue takes place and a choice is made, not much can be achieved, he believes.

EPA and especially the assistant administrator responsible for the Superfund program "have to take the lead in instigating the dialogue, in building a consensus. Porter didn't take it on. He is a very good engineer, but he wasn't a politician and he wasn't a policy person," Lucero says.

Porter believes that he "made a lot of tough decisions and got the program running at a high level." He also believes that he took a lot of unjustifiable heat, especially from the Congressional Office of Technology Assessment.

OTA and others have criticized the program for being too decentralized, "with no line of authority to headquarters." This has led, they say, to a situation in which there is no national consistency in the selection of cleanup remedies.

"A particular regional administrator may not come up with exactly the same remedy that another one has, given the same facts," Porter says. "Superfund is not an exact science. But probably more relevant is that the problems were not the same."

However, a Senate staffer argues that "Many things can be replicated at different sites. There are certain generic ways to proceed." Perhaps another dialogue is warranted given these different views of centralized versus decentralized management, and generic versus unique cleanup remedies.

Porter makes a case for his management by delegation, especially to regional EPA administrators. He contends that it has led to more site cleanups. In the first six years of the program, six sites were cleaned

up permanently. During Porter's reign another 44 sites were added to this list. This jump seems impressive until one realizes that EPA has more than 1000 Superfund sites to deal with.

Still there was improvement, not only in cleanups but also in the number of settlements with so-called responsible parties. "There were 85 settlements for remedial work in the first six or seven years of the program, and 55 in the past fiscal year," Porter notes. He attributes this increase to his delegation of responsibility, to his insistence that settlement negotiations end by a certain date, and to his aggressive use of "mixed funding." He calls mixed funding "a powerful tool" whereby EPA, the states, and responsible parties pay a portion of the cleanup.

Porter has a slew of numbers to back up his claims. The only problem is that Superfund generates a morass of numbers, and current EPA figures don't always agree with Porter's count. Also, says one critic, Superfund managers were "only interested in bean counting, which subtly undermined the program because the various EPA regional offices needed to meet targets without regard to quality."

This is not to say that Porter didn't redouble his efforts to ensure that good remedies were chosen. But, again the root of the criticism may be traceable to poor communications. As Porter explains, "We are all throwing around these numbers and often we are talking apples and oranges. One of the things I worked on very hard—but there is still plenty of room for improvement—is to do a better job explaining all these numbers."

Not all criticism lobbed at the program or at Porter's administration of it was unhelpful. Indeed Porter found Sen. Frank R. Lautenberg (D.-N.J.), who chairs the Senate Superfund, Ocean & Water Protection Subcommittee, quite constructive, especially his emphasis on meeting schedules. "Another constructive criticism from Sen. Lautenberg's subcommittee had to do with the turnover of young staff. We were very much aware of that, but some interesting ideas came out of some of the hearings," Porter says.

The staff turnover issue crops up in many studies of Superfund, the latest being Lautenberg's subcommittee report released just a few weeks ago. This report notes that Superfund staff turnover rates exceed those for other EPA programs and for the rest of the federal government as well. This results in a young, inexperienced staff with management responsibilities for a technically complex program.

Porter has noted correctly that some of the criticisms of the program are mutually exclusive. Superfund has been criticized for its inexperienced staff. But the program also has been criticized for using too many outside contractors in lieu of staff.

According to Porter, part of the turnover problem may have been solved by getting more responsible parties to do the actual cleanup work. These parties "are big companies that know how to run big projects, which takes care of the problem I had with the turnover among the young people," Porter explains.

But EPA staff still has to manage emergency cleanups and those long-term cleanups for which responsible parties cannot be found or where the parties refuse to do the cleanups. There is no question that with Superfund "EPA was given a Herculean task, made more difficult by the agency not being able to get the best people or keep a trained work force," Lucero says.

This leads Lucero to frame another of his fundamental issues. "What can EPA do to work around this institutional fact of life? Are internal review teams the answer?" Lucero asks. He doesn't answer these questions, merely offers them as the basis for dialogue.

As much as Porter applauds Sen. Lautenberg, he damns OTA. "The only group I felt was consistently unfair was OTA, and specially Joel S. Hirschhorn," who authored OTA Superfund studies, Porter says. He accuses Hirschhorn of gross oversimplification by extrapolating from a few sites to the whole program. He faults OTA reports for not being peer reviewed, and for containing factual errors. He says Hirschhorn carried out "over-the-telephone engineering. And since he is not a design or project or construction engineer he tends to oversimplify things."

Hirschhorn says, "Every report we put out has to go through external review, sometimes twice." As for the charge of over-the-telephone engineering, he responds, "I do a detailed analysis based on getting information from many different sources inside and outside the government." As to the charge of errors, Hirschhorn answers, "There is

Superfund scoreboard

Number of Superfund sites	1,173
Potential Superfund sites	30,844
Number of emergency cleanups	1,837
Number of sites cleaned up	50
Number of Superfund sites deleted from the National Priority List	26
Remedial investigation (RI)/feasibility studies (FS) under way	681
Record of decisions (or RI/FS completed)	438
Remedial action at Superfund sites	
Under way	174
Completed (at portions of sites)	103
Total Superfund money authorized by law	$10.1 billion
Amount spent to date	$4.5 billion
Number of judicial settlements	101
Amount of settlement recoveries	$128 million
Total of cost recovery action initiated at 273 sites	$343 million
Enforcement actions	702
Amount of enforcement actions	$2.21 billion
Administrative orders to responsible parties	660

EPA uses nine criteria for selecting cleanup remedies

The following criteria are listed in the proposed National Contingency Plan, Superfund's master plan, but are not legally binding. They are, however, being used by EPA staff.

- Protection of human health and the environment
- Compliance with all applicable local, state, and federal requirements
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community reaction

not one case in which EPA has ever documented a mistake made in OTA reports."

Porter was particularly unhappy with OTA's review of EPA's remedy selections for site cleanups. He says OTA considered only permanence and treatment, not all of the nine criteria he instructed his regional administrators to use. The criteria Porter refers to are not part of Superfund's master plan, the current National Contingency Plan, and, therefore have no force of law. But they are included in EPA's proposed NCP, which has not yet been sent to Congress as required by the reauthorized 1986 Superfund law.

Though Porter lays much importance on these criteria, others have faulted them. Early says, "They have allowed too much discretion to decisionmakers, which isn't justified by the 1986 Superfund revisions." A Senate aide says, "The legacy Porter temporarily leaves is a selection of remedy process that uses nine meaningless criteria. This is the core of the problem. There are no rules of the game because the nine criteria have no meaning. This leads to inconsistency within and across regions."

Porter sees "no need for major changes in the program's fundamentals—in remedies selected, or the way contracting is done—over the next couple of years. The framework is good; there is only need for improvement around the edges." The new administration at EPA appears to be rewriting the rules of the Superfund game, however.

EPA has undertaken a three-month review of the program, soon to be released to the public. As part of this review, Lewis S. W. Crampton, special assistant to the EPA Administrator, has been reading every criticism of the program ever written, including OTA's. "The OTA reports have been very valuable in putting together this Superfund management review. Sometimes the rhetoric has pinched a bit, but Hirschhorn hasn't lied or stretched the truth," he says.

This review will lay out Administrator Reilly's "management philosophy and vision for operating this program," Crampton explains. "There will be a bias toward strong enforcement, greater citizen participation in the program, and more permanent remedy selections. The review will resolve many contradictions: whether to do pristine cleanups, whether it will be a centralized or decentralized program," he adds.

Hirschhorn: studies well documented

"The core of our approach to implementing Superfund will be to take early action using emergency removal authority. Then to follow this with a series of corrective actions so that the site meets public health standards," Crampton says. In what he calls an "enforcement-lead process," he expects more responsible parties to do the cleanup but with better quality review from EPA.

EPA needs to declare publicly that Superfund is a long-term project, requiring another "one or two reauthorization cycles before the job is done. The agency must stop trying to achieve speed for speed's sake. It must try to inject more efficiency and quality into the program," Crampton says. Most important, the agency and Congress must enter into a dialogue so that there are "mutual expectations for the program," he says.

The fervent hope is that EPA's management review will clearly delineate a better way to implement Superfund with quality and efficiency and thereby lay to rest past criticisms. □

Clean Sites offers recommendations for Superfund upgrade

Clean Sites Inc., a private, nonprofit organization whose aim is to solve the U.S.'s hazardous waste problem, has termed the current Superfund program viable—but the Environmental Protection Agency must mend its ways. Specifically, EPA must change the way it implements the program.

With that in mind, Clean Sites offers EPA several recommendations, which former director of Superfund enforcement Gene A. Lucero finds commendable. "If a number of the suggestions are implemented, the program would run 20 to 30% better. Add an effective, politically connected person and it will run 50% better." Clean Sites' recommendations are:

- Increase responsible-party cleanups by maximizing enforcement and settlement, including an accelerated implementation of a strategic enforcement program, and pursue vigorously a limited number of "good" cases rather than merely generating more cases.
- Improve the remedy selection process by a commitment to early site action through expanded use of removal actions at Superfund sites. Where there is significant uncertainty about the remedies being considered, EPA should require an appropriate array of treatability studies to be part of the remedial investigation/feasibility study process.
- Manage the program for optimal progress by delegating site-specific decision-making authority to the regions. The position of Superfund remedial project manager should be upgraded. To avoid further delay, headquarters and regional Superfund offices should not be reorganized now.
- Define new measures of program success. New tracking measures should include the speed with which EPA is cleaning up sites, the quality of the cleanups, and the number of cleanups financed by responsible parties. EPA should provide the public with information that is readily available and clearly understandable.

Process Catalysts Enjoy Surging Market

Bruce F. Greek, C&EN Houston

Screening pelletized auto emission catalysts at Degussa's Calvert City, Ky., plant

Nearly every segment of the catalyst business is growing. Strong demand for chemicals and polymers, for fuels from petroleum, for products that reduce pollution, and for biological materials is increasing consumption of catalysts. Resurging markets for catalysts also are providing new incentives for research and development in catalysts and in processes that require their use.

The worldwide market for catalysts this year likely will be valued at more than $5 billion. Most of them will be used in three major industries: chemical processing, petroleum refining, and pollution control.

From 35 to 40% of catalysts sold worldwide this year will be used in the U.S., amounting to about $1.9 billion worth. For the first time, the value of catalysts consumed in pollution abatement uses is expected to exceed the value of catalysts consumed in petroleum processing. Dollarwise, that means sales of pollution abatement catalysts will total about $650 million, petroleum refining catalysts just a little less, and chemical processing catalysts about $575 million, according to a study of catalysts by consulting firm Freedonia Group, of Cleveland.

In Western Europe, about $900 million worth of catalysts will be used this year in chemical processing, crude oil refining, and auto emission control, according to estimates in a just-completed study by Frost & Sullivan, a New York City consulting firm. For these three categories, catalysts used in Western Europe will nearly double in value by 1993, to nearly $1.8 billion, the firm forecasts. For 1989, the market breakdown for Western Europe will be about $425 million for chemical processing catalysts, $210 million for refining catalysts, and $550 million for emission control catalysts.

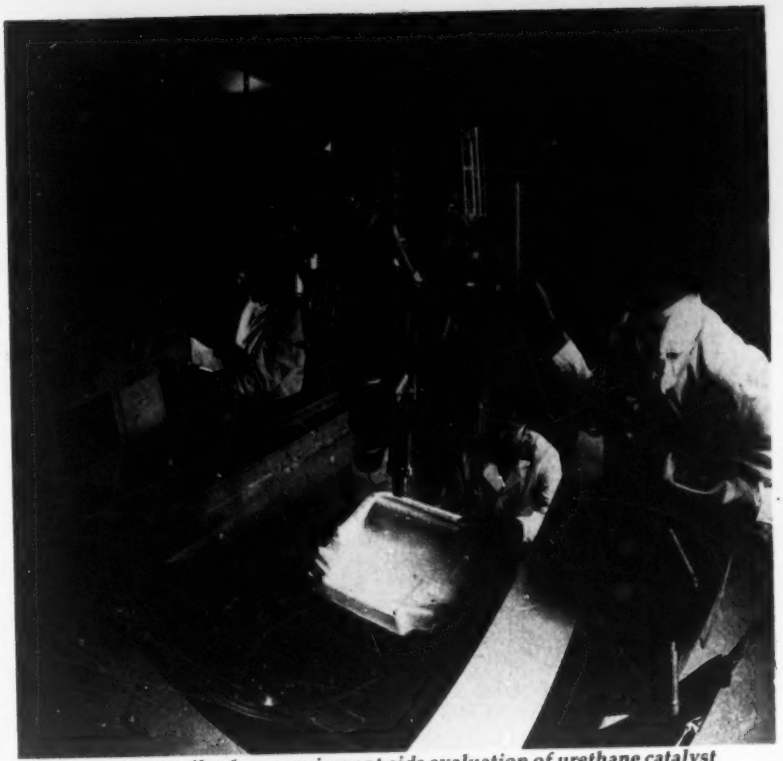
Nevertheless, in terms of physical volume, catalyst consumption in the U.S. and Western Europe continues to be dominated by petroleum refining. Refining catalysts account for more than 90% of the total catalyst volume because of large quantities of sulfuric and hydrofluoric acids used in alkylation processes. The physical volume of catalysts used in pollution control, ex-

cluding carriers for the active catalysts, is extremely small (less than 0.003% of total volume) because of high activity and cost of platinum and other metals of the platinum group used as the active catalysts.

The platinum group metals—platinum, palladium, rhodium, and ruthenium—will account for about 40% of the value of catalysts consumed in the U.S. this year. A small amount of silver used alone or as derivatives will slightly increase the share of noble metal catalysts. Nearly all platinum group metal catalysts are used for pollution abatement, and nearly all of that, 95%, is for catalytic devices in automotive exhaust systems.

Longer term, pollution control (largely using platinum group metals as the active catalysts) will take an increasing share of the value of catalyst materials. Behind their increasing value, and increasing prices, will be greater demand driven by worldwide efforts to reduce air pollution and, to a lesser extent, by increasing use of these metal catalysts in the chemical and refining industries. By 1992, for example, pollution control will account for 40 to 45% of the value of catalysts sold in the U.S., and this share will rise to more than 50% by the year 2000, according to the Freedonia Group study. Demand for industrial pollution control using catalytic processes is growing faster than motor vehicle pollution control, but the industrial segment is growing from a base that is 5% of the volume used in motor vehicles.

Physical volume of platinum group metals consumed as catalysts for all uses is forecast by Freedonia Group to increase an average of 5.1% annually through 1992, using 1987 as the base year. The value of of these metals will increase 14% annually during this period. Physical volume growth for most other catalyst materials will average 1.4% annually because the share of the commodity chemicals is relatively large. Value growth for other materials, excluding the commodity chemicals and platinum group metals, will be in the 2 to 3% range, except for peroxides, which will average 6.7% for the 1987–92 period.



At Air Products, pilot foam equipment aids evaluation of urethane catalyst for automotive application

Total consumption of platinum group metals for all uses in the U.S. peaked in 1985 at more than 2.27 million troy oz, according to the Department of the Interior's Bureau of Mines. By 1987, the latest year of available data, consumption had declined to 1.94 million troy oz. In addition to automotive emission catalysts, these metals have applications in, among others, chemical processing, crude oil refining, electrical components, jewelry, and dentistry. U.S. imports of platinum group metals have been holding at about 4 million troy oz, and exports of the metals have declined to about 700,000 troy oz, from 1.3 million in 1983.

Automotive catalysts accounted for 43% of all U.S. consumption of these metals in 1987, according to Bureau of Mines figures—including 73% of both platinum and rhodium. Chemical processing required 5.3% of platinum group metal consumption that year, and petroleum refining only 3.2%. Other uses, such as electrical components, jewelry, and dentistry took the remaining share of about 47% of the total. Because these metals have few competitors in automotive uses and in uses other than chemical and refining, prospects for their consumption seem unlikely to depend on supply and selling prices, unless prices rise greatly or imports are cut off.

Other commercially significant materials used as catalysts (other than the noble metals) include various base metals (alone or as their oxides), zeolites (complex aluminosilicates), peroxides (not technically catalysts but free radical initiators), the commodity chemicals, and miscellaneous others, including rare-earth elements.

In addition to active catalytic agents, large quantities of carriers are used in preparing catalysts for use. Some of the carriers—aluminum oxide, for example—also provide catalytic activity and, with another catalytic material, may be considered to be components of a bifunctional catalyst. Other carriers are clays, many kinds of minerals (such as silicas and aluminas), and zeolites. The difference between zeolite carriers (or supports) and zeolite catalysts often depends on physical properties of these materials. Developing carriers and supports for catalysts is becoming as much a science as is catalyst development.

The numerous manufacturers of

catalysts offer a wide range of materials and services. Many producers make catalysts only for merchant sale. Others, such as oil companies whose main products are fuels, make catalysts for both internal use and for sale. Some producers only custom-make catalysts in response to inquiries.

Some distribution companies sell both U.S.- and foreign-produced catalysts. The catalyst business is quite fragmented, with many components frequently competing with each other.

After catalyst demand declined in the early 1980s, when both chemical and petroleum refining markets slumped, producers took various cost-cutting steps, such as rationalizing capacity and limiting development work. In the past two years, as processing increased and product profit-margins improved, a resurgence in capital investment and business activity resulted. Capacity to manufacture all kinds of catalysts and to develop new catalysts and processes continues to expand under pressure of the currently strong demand for chemicals, fuels, and other products. Many foreign catalyst producers have entered the U.S. market during this decade, largely through acquisition, but also by setting up their own marketing operations. The long-time U.S. producers also have expanded their catalyst product lines and capacities through acquisition and by building new units.

West Europe market will soar for emission control catalysts . . .

$ Million	1987	1990	1993
Chemical processing	$403	$ 432	$ 463
Crude oil refining	207	216	235
Emission control	248	650	1085
TOTAL	$858	$1298	$1780

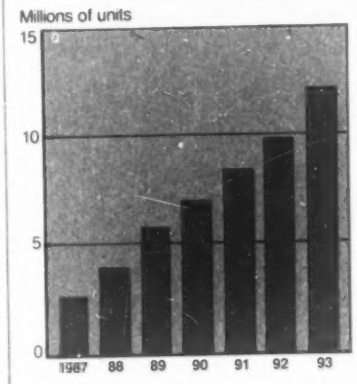
Source: Frost & Sullivan

. . . but will grow slowly for chemical processing catalysts

$ Million	1987	1990	1993
Polymerization	$151	$163	$178
Oxidation	108	111	115
Organic synthesis	46	51	56
Synthesis gas	44	48	51
Hydrogenation	43	47	51
Dehydrogenation	11	12	13
TOTAL	$403	$432	$463

Source: Frost & Sullivan

West Europe market rising for auto emission catalysts



Source: Frost & Sullivan

Among the rash of developments in the catalyst business is this week's announcement by Degussa of an expansion program. Degussa plans to build a new facility in South Plainfield, N.J., to make a wide variety of precious metal catalysts for use in fixed-bed chemical processes. At the same site, Degussa will build its first catalyst development and technical center outside West Germany. At Calvert City, Ky., the company also plans to expand a plant recently acquired from Air Products & Chemicals that makes automobile emission-control catalysts. This expansion follows an earlier expansion at Degussa's Burlington, Ontario, plant where monolith catalysts are made for auto emission control.

Another recent development in the catalyst business is the breakup and sale of Harshaw-Filtrol, once owned by KaiserTech, a leveraged buyout of the former Kaiser Chemical. Harshaw-Filtrol was split because of concerns of possible antitrust actions by the U.S. Justice Department. Engelhard purchased the Harshaw part more than a year ago and has nearly completed the integration of Harshaw. The addition brings many base metal catalysts into Englehard's product line, thereby expanding the line to what the company believes is the broadest range of catalysts in the world. The company also has just announced two new series of fluid catalytic cracking catalysts designed to provide higher octane-value cracked gasoline while retaining optimum yield from feedstocks.

The remaining Filtrol Corp., still owned by KaiserTech of Oakland, Calif., apparently will become a part of Akzo. In April, Akzo reached an agreement with KaiserTech to purchase Filtrol, a large producer of catalysts for fluid catalytic cracking. The Filtrol addition is expected to broaden Akzo's catalyst business, which includes various olefin polymerization catalyst systems and free radical initiators for vinyl chloride polymerizations, as well as an extensive line of cracking catalysts for petroleum refining.

Davison Chemical, a division of W. R. Grace, is another company with an expansion program for fluid catalytic cracking catalysts. Construction plans are under way for a plant with capacity of 45,000 tons per year of catalysts for fluid catalytic cracking. The plant will be located at Davison's manufacturing complex at Lake Charles, La.

Other changes are occurring in this small but vital industry made up of about 100, mostly small, companies, most in the U.S. Many of the 30 to 40 larger catalyst companies are subsidiaries of chemical and oil companies. Five companies make catalysts for motor vehicles, and they sell to almost as few customers. About twice as many companies are major suppliers to the refining industry, including some of the oil companies. The chemical catalysts producers are much more fragmented, with many small producers making specialty catalysts for a limited market of a few reactions. The life of the small producing company frequently is short, as the developing product lines attract large catalyst companies. Small companies often are acquired by larger companies headquartered both in and outside the U.S., as a way to enter another part of the catalyst business or to expand capacity in an existing product line.

Methods of marketing catalysts are changing rapidly, too. In the past, suppliers provided data about their catalysts, leaving the custom-

er to evaluate the catalysts and possibly to request an adaptation to a particular need. Or, customers would develop catalysts or buy processes under license and ask manufacturers to make the desired catalysts.

Marketing catalysts now requires a clear understanding of the customer's needs, a constant improvement in catalyst performance, and much customer service. Most catalyst sales staffs are technically trained, and normally they deal with the development, engineering, and technical operating personnel rather than with centralized purchasing departments of customer companies. In new commercial catalyst development, collaboration between suppliers and customers occurs on levels as high as those of other technical aspects of the chemical and refining industries.

Strategies for marketing catalysts vary significantly among the major consuming industries. In the automotive industry, for example, the few customers and the few alternatives to existing catalysts for emission control make the barrier high for entry by a new supplier. The petroleum refining industry has more customers than the automotive industry, but relative size of the companies is still large. Marketing to refiners requires dealing with several large and geographically diverse organizations, many of which operate quite similar units and processes. In contrast, the many more chemical processing companies range from small to very large, requiring marketing methods able to handle a wide spectrum of customer needs.

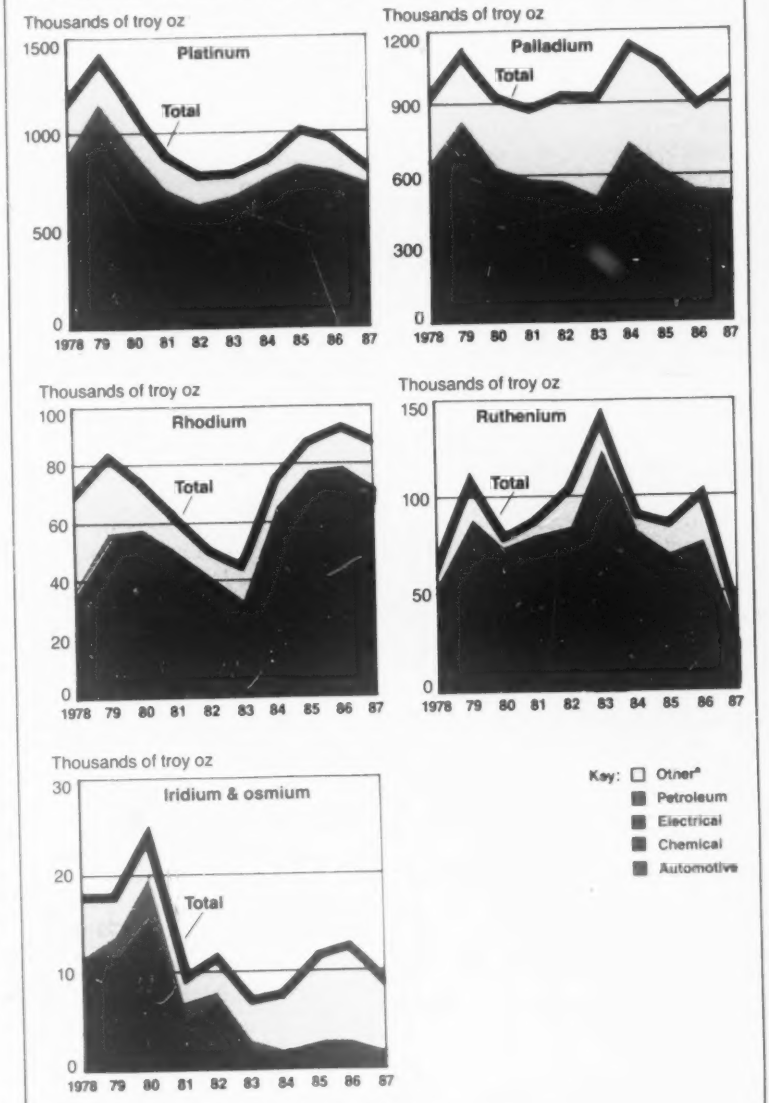
Consistent performance of catalysts means more today than a few years ago, because most companies using catalysts have become highly quality conscious. If one company's catalysts have established a performance record of consistency and efficiency, then, to gain a sale, a different supplier must show that a change to its catalysts will give more than a moderate cost savings.

Some catalyst producers entered the business to make catalysts for chemical and refining processes that they had developed, either alone or with an engineering or research organization. They continue to develop processes for these industries and catalysts for the processes, as a way to utilize expertise built up over time. This kind of process development has led to expansion in the catalyst business and is expected by many industry sources to be a major driving force for future catalyst business expansion.

Chemical processes that use catalysts include polymerization, oxidation, reforming (or synthesis gas production), hydrogenation, dehydrogenation, and synthesis (or alkylation). Frequently, two distinct chemicals are used as catalysts. For example, in olefin polymerization using Ziegler-Natta technology, an aluminum alkyl and a titanium halide make up the system. In some cases, a reaction occurs between the components of the catalyst system to give a third member of the system.

Conversion processes in petrole-

Use of most platinum group metals has declined recently



[a] Jewelry, dentistry, miscellaneous. **Source:** Department of Interior

Various factors affect potential use of enzymes in industry

Advantages	Limitations
Catalytic efficiency	Cost
Few by-products	Lability
Mild conditions	Product inhibition
Reaction selectivity	Rigid selectivities
Stereoselectivity	

Source: Perry A. Frey and Hans Liao, University of Wisconsin

um refining require catalysts, whereas separation processes do not use them, but separations are essential in providing the feedstocks for the conversion processes. Many of the catalytic processes of refining are the same as those used in chemical processes but are used to different degrees. Polymerization, for example, was an important refining process during the 1930s, but now it is a minor part of petroleum processing. Cracking, seldom used in chemical processing, continues to be the most important catalytic process in refining. Other catalytic refining processes are alkylation (which has largely supplanted polymerization), hydrotreating in several forms, and reforming (including isomerization).

Polymerization processes using catalysts (including free radical initiators) account for the dominant share of the value of catalysts used in chemical processes, at about half of the total, according to another study on the U.S. markets for catalysts used in chemical processing and petroleum refining prepared by Frost & Sullivan. Catalysts used in polymerizations are more expensive than catalysts used in several other chemical processes. However, as their activities, or efficiencies, continue to rise rapidly, they are holding down, and maybe reducing, those costs. Industry sources expect efficiencies of polyolefin catalysts on the average to be doubled over the next five years.

Estimates of efficiencies of polymerization catalysts vary widely. These estimates, forecasts for output of various polymers, and projections of costs of catalysts form the basis for forecasting both the value and quantity of catalysts to be used in the future. The forecasts for catalyst use generally are made for the active catalysts and do not include the relatively large quantities of support materials that are a part of most catalyst systems.

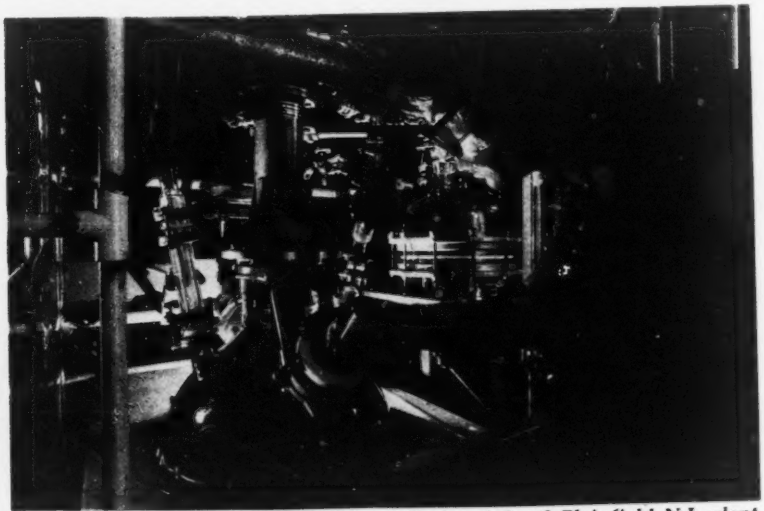
For example, in the polyolefin catalyst industry, the Ziegler-Natta systems produce about 10,000 lb of polymer per lb of catalyst (active agent and support), according to Frost & Sullivan. This efficiency is forecast to double over the next five years. The Phillips process for making high-density polyethylene may have an efficiency of about 10,000 lb per lb of a chromium oxide-type catalyst.

In polypropylene manufacture, using Ziegler-Natta technology, polymer production jumped from less than 1000 lb per lb of catalyst in the early commercialization stages to 20,000 lb per lb currently, with an additional step to 40,000 lb per lb of catalyst now under way. When polypropylene initially was commercialized, the polymer was washed to remove the spent catalyst, especially the titanium halide, because it gave undesirable color to the polymer. Now, with few exceptions, polyproplyene isn't washed because the residual catalyst content is so small that it gives few undesirable properties.

Other major volume polymers—such as low-density polyethylene (and now linear low-density polyethylene that uses a Ziegler-Natta-type catalyst system), polyvinyl chloride, and polystyrene—are made by using a free radical initiator system based on organic peroxides. Most of these polymerizations consume initiators or catalysts at the rate of about 1 lb per 1000 lb of polymer. The organic peroxides used cost $2.00 to $3.00 per lb.

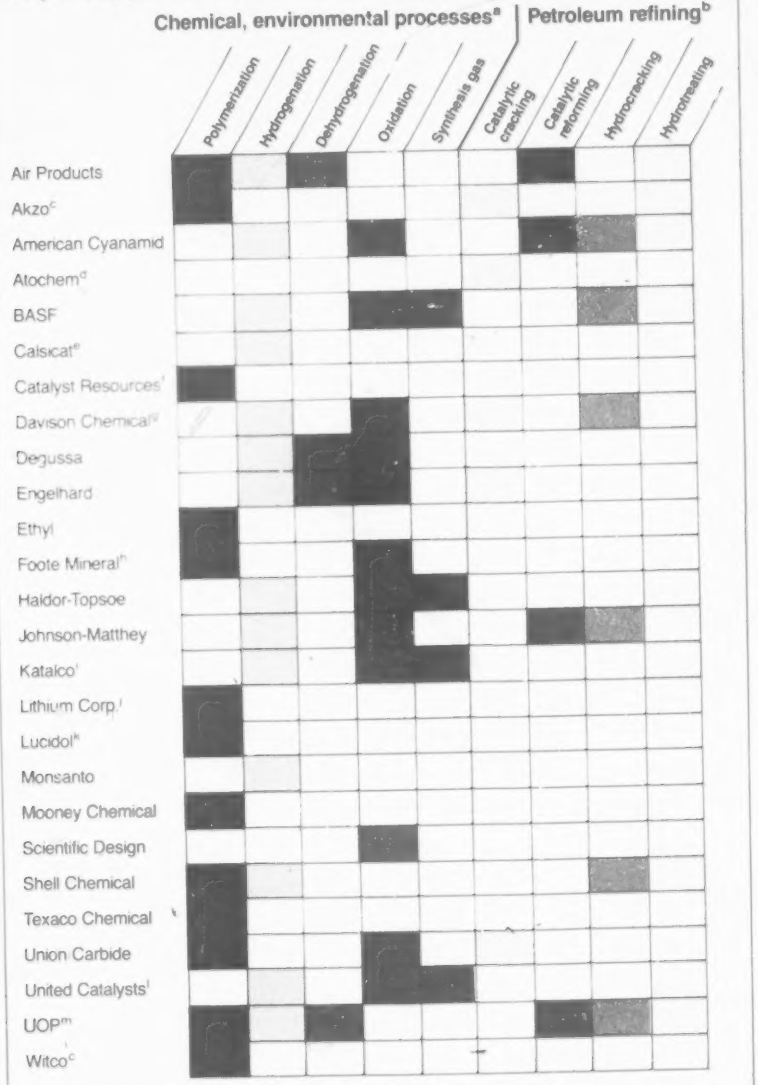
Oxidation catalysts are a distant second to polymerization catalysts in market value. Production of several large-volume chemicals incorporates oxidation as the key step in their manufacture: ethylene oxide, nitric acid, sulfuric acid, phthalic anhydride, acrylonitrile (using the ammoxidation process), formaldehyde, and vinyl chloride (using the oxychlorination process). Most of the catalysts used in commercial chemical oxidation processes are metals or metal oxides on various supports.

Sulfuric acid is by far the largest volume chemical produced by oxidation. With few exceptions, most sulfuric acid produced in the world is made by burning sulfur to produce the dioxide and then oxidizing the dioxide to the trioxide using a vanadium pentoxide catalyst on a diatomaceous earth carrier. Sulfuric, in turn, can be used as a catalyst, and worldwide demand for it in this use was between $10 million and $14 million in 1988, according to Monsanto's Enviro-Chem Systems. Growth in demand for these catalysts is forecast to be slow. Improvements continue to be made in sulfuric acid catalysts aimed at reducing resistance to gas flow with-



Worker checks catalyst salt production at Degussa's South Plainfield, N.J., plant

Major suppliers offer catalysts for variety of processes



a Excludes producers of commodity chemicals—sulfuric, hydrofluoric, and phosphoric acids, aluminum trichloride, and others—used as catalysts. b Excludes using commodity chemicals such as sulfuric and hydrofluoric acids. c Various subsidiaries. d Subsidiary of Elf Aquitaine. e Subsidiary of IMC. f Subsidiary of Phillips Petroleum. g Subsidiary of W. R. Grace. h Owned 80% by Newmont Mining. i Subsidiary of ICI. j Subsidiary of FMC. k Division of Pennwalt. l Subsidiary of Süd-Chemie. m Subsidiary of Allied-Signal. **Sources:** Frost & Sullivan, company data

out loss of properties such as activity, durability, and life.

The top-ranking oxidation catalyst, in terms of value of shipments last year, is silver oxide, used to speed manufacture of ethylene oxide. More than 6 billion lb of ethylene oxide will be made this year using a catalyst of silver oxide on an alumina support. Over the average three-year life of the catalyst, consumption is low because most of the silver is recovered during reprocessing of the catalyst. In a new ethylene oxide plant, the cost of the catalyst represents a significant part of the plant investment.

Nitric acid manufacture is next in size to ethylene oxide in value of catalyst consumption. To make nitric acid, ammonia is oxidized (burned) over a platinum group metal gauze or screen, often at the same site where the ammonia itself is manufactured. Efforts are continually made to reduce the loss of metal—mostly platinum with a small amount of rhodium and palladium—to below 0.01 troy oz per ton of nitric acid through process variations that reduce the pressure. Cost of catalysts for nitric acid production annually in the U.S. totals about $20 million.

Production of phthalic anhydride from *o*-xylene or naphthalene also uses vanadium oxide catalysts. Newer technologies for this oxidation use fixed-bed catalyst systems that reduce catalyst losses from levels that occur in older fluid-bed technologies.

Other chemical oxidations include making formaldehyde from methanol using catalysts such as iron and molybdenum oxides, and sometimes with chromium as a promoter or activator, or with silver and copper gauzes. To make acetaldehyde from ethylene, a palladium-copper chloride solution is used. Copper chloride also can be used in oxychlorination to make vinyl chloride. Ammoxidation of propylene to acrylonitrile may use other metals such as antimony as the active agent in the catalyst system.

Alkylations, sometimes called chemical synthesis, are dominated by two large-volume products. Ethylbenzene (the precursor of styrene) and cumene (the precursor of phenol and acetone) are made using aluminum chloride and phosphoric acid as catalysts. The quantities of these catalysts consumed in making the alkylation products is relatively large, possibly totaling 100 million lb this year, but their cost is low, being well under $1.00 per lb.

Steam reforming (or manufacture of synthesis gas containing carbon monoxide and hydrogen) precedes the making of two major-volume chemicals—ammonia and methanol. Several different catalyst systems are used to speed synthesis gas manufacture from steam and methane or coal. The active catalysts are mainly metals such as iron, nickel, cobalt, and molybdenum and their oxides. Refinements in these catalysts have been developed since early this century, following commercialization of synthetic ammonia. Demand

growth for these catalysts is slow because of improvements in efficiencies and the low average growth in use of ammonia and methanol.

Hydrogenation and dehydrogenation process catalysts make up about 10% of the chemical processing catalysts market. About half of the market is in nickel catalysts used in hydrogenation to saturate fats and oils. Platinum or palladium on various supports is widely used to hydrogenate benzene to cyclohexane. Other catalyzed hydrogenations make cyclohexanone from phenol, toluenediamines (for isocyanates) from dinitrotoluenes, and many kinds of fatty amines. The most important dehydrogenation process is making styrene from ethylbenzene using an iron oxide catalyst. Growth in catalyst use for the various hydrogenation and dehydrogenation processes will be slow, according to the Frost & Sullivan study.

Many other smaller volume chemical processes involve use of catalysts. Among the more important ones are hydration, dehydration, hydroformylation, and condensation. Although some of these processes may have large fractional gains in catalyst use, the total will remain small compared with other processes and will have small impact on the total catalyst market.

Important petroleum refining processes that use catalysts fall into four basic groups—cracking, alkylation, reforming (including isomerization), and hydrogenation. In petroleum refining, the largest catalyst market in terms of dollars is catalytic cracking, expected to be worth $250 million to $300 million this year. The largest refining catalyst market in terms of quantity is alkylation, requiring about 4 billion lb of mineral acids worth about $150 million.

Fluid catalytic cracking has almost entirely replaced thermal cracking of petroleum in the U.S., except for two severe forms of cracking—coking and viscosity breaking. And zeolites have replaced almost all other kinds of catalysts in cracking. A small number of fixed-bed catalytic cracking facilities remain, but their operation is limited because of the need to halt cracking from time to time to regenerate the catalyst bed by burning off deposits of coke and heavy hydrocarbons.

Most fluid catalytic cracking catalysts are proprietary zeolites on silicates. The composition of the zeolites varies widely, as do the kind of additives put on the catalysts to improve cracking. Use of additives in cracking catalysts can boost the octane value of the cracked gasoline, with minimal reduction in yield based on feedstock going to the cracking unit. Catalysts that improve the motor octane value of cracked gasoline are especially important since the phaseout of lead antiknock additives.

Minor variations in catalysts for fluid catalytic cracking units are used among refineries. The variations are a result, in part, of the competition to gain octane value in finished gasoline at the lowest cost. Fluid catalytic cracking competes with catalytic reforming and with use of compounds containing oxygen that have high-octane values, such as methyl *tert*-butyl ether.

Consumption of fluid catalytic cracking catalysts varies with each unit. Some of the newer units may consume a tenth of the catalyst volume that older units consume. Other influences on catalyst consumption include the activity of the cata-

Environmental catalysts will lead demand growth . . .

$ Million	1987	1992	2000	Average annual growth, % 1987-92
MARKET				
Emissions & pollution control	$ 501	$ 985	$2060	14.5%
Motor vehicles	476	900	1730	13.6
Industrial	25	85	330	27.7
Petroleum refining	596	710	900	3.6
Chemical manufacture	534	640	840	3.7
TOTAL	**$1631**	**$2335**	**$3800**	**7.4%**
CATALYST TYPE				
Noble metals	585	1095	2200	13.4
Platinum group	571	1080	2180	13.6
Silver	14	15	20	1.4
Base metals	401	460	560	2.8
Zeolites	282	325	390	2.9
Peroxides	210	290	465	6.7
Commodity chemicals[a]	135	145	160	1.4
Others	18	20	25	2.1
TOTAL	**$1631**	**$2335**	**$3800**	**7.4%**

. . . but volume growth will be smaller than value growth

	1987	1992	2000	Average annual growth, % 1987-92
CATALYST TYPE, millions of lb				
Base metals	212	240	255	2.5%
Zeolites	333	390	515	3.2
Peroxides	42	50	60	3.5
Commodity chemicals[a]	3905	4135	4275	1.2
Others	12	15	20	4.6
TOTAL	**4504**	**4830**	**5125**	**1.4%**
NOBLE METALS, thousands of troy oz				
Platinum Group	1306	1675	1980	5.1
Platinum	882	1154	1405	5.5
Palladium	345	420	460	4.0
Rhodium	59	89	105	8.6
Others	20	12	10	−9.7
Silver	2500	2250	2200	−2.1
TOTAL	**3806**	**3925**	**4180**	**0.6%**

a For example, mineral acids. b Noble metals excluded because of [illegible] Source: Freedonia Group

lysts, type and properties of the feedstock to the unit (such as its sulfur content and gravity), whether or not the feedstock has been treated to improve its properties, and severity of operation of the cracking unit. Consumption is believed by industry sources to be slowly increasing because refinery fluid catalytic cracking units are being operated more severely and with higher throughput to meet gasoline demand and because the feedstocks are heavier and more contaminated with sulfur, nitrogen, and metals.

Consumption of cracking catalysts this year is forecast to range between 0.15 and 0.25 lb per barrel of feedstock. With catalytic cracking units processing nearly 5 million bbl per day, catalyst consumption could reach 400 million lb.

Nevertheless, many changes could occur in catalyst consumption this year. One uncertainty stems from the planned decrease in use of butane in gasoline to reduce its vapor pressure and emissions into the atmosphere. The butane could be put into fluid catalytic cracking units to produce more olefins and isobutane for alkylation or for chemical uses. Another uncertainty is the possible use of more residual oil in catalytic cracker feedstocks to reduce the amount of this oil that must be sold in competition with lower cost natural gas. The heavier and generally more contaminated residual oil, if used, would tend to increase catalyst consumption in cracking units.

Catalytic reforming of various naphthas converts these low-octane petroleum fractions to high-octane, highly aromatized gasoline components. Some of the aromatics are separated from the reformate to supply aromatics used as chemical raw materials. About half of the U.S. components of gasoline now come from catalytic reforming. Currently, platinum and another metal—often rhenium or iridium—account for

Key properties determine performance of catalysts

Activity. Measured as the quantity of reactant in contact with a catalyst under given process conditions.

Physical Stability. Measured by at least three standards: retention of porosity and of structure under given process conditions and retention of mechanical strength, an indication of resistance to handling forces.

Regenerability. Measured as how well catalysts regain activity and selectivity after removal of deposits of substances that reduce such properties.

Selectivity. Measured as efficiency of catalysis by determining yield of products relative to quantity of reactants.

Stability. Measured as how well catalysts retain activity and selectivity over their life span.

Source: Frost & Sullivan

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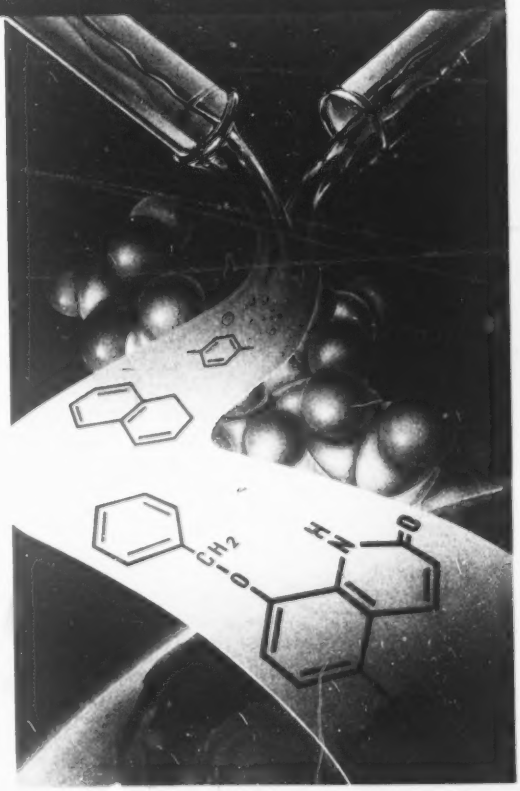

Various Akzo catalysts

most reforming catalysts, having supplanted the initial reforming catalysts made of silica-molybdena used in the 1950s and 1960s. These catalysts are expensive, but the quantity consumed per barrel of gasoline is small, making the value of these catalysts a tenth of that of catalytic cracking catalysts.

The longer term outlook for reforming catalysts is better than it was three years ago. Reduction in gasoline volatility, by reduction of high-octane-value butane in gasoline, requires that other high-octane components replace butane. Aromatics in reformate are expected to be one of two major sources of these components. To increase output of reformate, the catalytic reforming units will be operated more severely, which will reduce yields and consume more catalyst.

Alkylation will be another source of additional high-octane components. Almost all refinery alkylation processes that combine a small olefin (butene) with a small paraffin (isobutane) to make a larger paraffin in the gasoline range of hydrocarbons are catalyzed with either sulfuric or hydrofluoric acids. The petroleum refining consumption of these acids, although large

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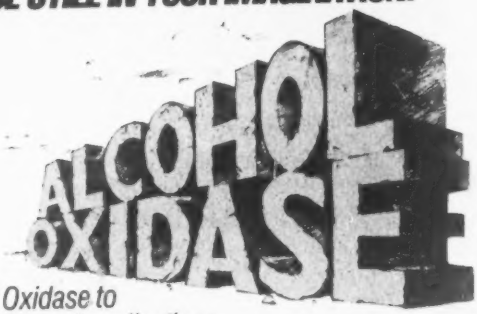

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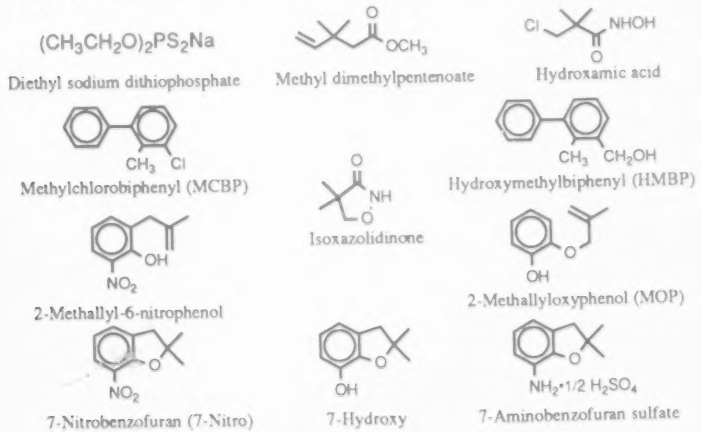

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Demand for petroleum refining catalysts will grow steadily

$ Million	1982	1987	1992	2000
Catalytic cracking	$235	$260	$310	$400
Alkylation	140	144	165	190
Hydrotreating	65	88	105	130
Hydrocracking	38	65	80	110
Reforming	20	32	40	55
Other	4	7	10	15
TOTAL	$502	$596	$710	$900

Millions of lb	1982	1987	1992	2000
Catalytic cracking	351	376	440	530
Alkylation	3885	3900	4125	4270
Hydrotreating	26	30	35	40
Hydrocracking	3	5	6	8
Reforming	4	5	6	8
Other	1	2	3	4
TOTAL	4270	4318	4615	4860

Source: Freedonia Group

in volume relative to consumption of other catalysts, is a small part of total consumption of these acids. Demand for these acids as alkylation catalysts varies partially with the level of operation of alkylation units. Alkylation varies with a refinery's supply of suitable olefins and paraffins.

Two catalyzed treating processes using hydrogen are growing slowly as consumers of catalysts. Hydrotreating consumes several times the volume of catalysts that hydrocracking does, because hydrotreating almost entirely uses base metal catalysts. The value of hydrotreating catalysts is only about 50% more than the value of hydrocracking catalysts, because some platinum group metals are used in hydrocracking catalysts. Hydrogen supply in refineries and competition from other processes, such as catalytic cracking and reforming, had been limiting growth of these two processes.

A more favorable outlook for these processes could boost catalyst consumption. The quality of crude oil for making gasoline generally will decline, causing refiners to hydrotreat feedstocks having higher contents of sulfur and nitrogen compounds. Hydrotreating (or simply, hydrogenation) removes the sulfur and nitrogen atoms. It also saturates part of the olefins and removes oxygen-containing compounds. A hydrotreated gas oil often is *the*

feedstock to a catalytic cracking unit. Hydrotreating will have to be increased if lower sulfur specifications are required for diesel fuel and other heavier fuel oils.

Hydrocracking, which includes some hydrotreating, is used to reduce the higher molecular weight hydrocarbons that are a big part of the bottom of a barrel of petroleum. Hydrocracking most often is used to prepare better feedstocks for catalytic cracking and reforming units. Usually, platinum and other similar metals on an alumina support are used, but base metal catalysts of nickel, cobalt, and molybdenum also may be used. The more expensive platinum group metals cause a much higher unit value for hydrocracking catalysts than for hydrotreating catalysts.

In the mid-1980s, hydrocracking was growing slowly because of a temporary increase in supplies of lighter, sweeter crude oils. The shift toward heavier sour crudes and the need for reformate, alkylate, and cracked gasoline now is starting a resurgence in hydrocracking. Better catalysts, however, will hold down consumption increases.

Tunnel furnace at Haldor-Topsoe's catalyst plant in Frederikssund, Denmark

Isomerization, a relatively old refining process, is gaining favor again as the need for alkylate increases. This process usually is used in refineries to convert C_4 to C_8 straight chain hydrocarbons, most of which have relatively low octane values (*n*-heptane is the standard value for zero research octane number), to branched chain hydrocarbons with higher octane values. The sources of these hydrocarbons are natural gas liquids and the light, straight run gasoline from the initial crude oil distillation. Product from isomerization units can be separated and the heavier fraction, with an octane value of 75 to 85, can go to gasoline blending. The lighter fraction can go to an alkylation unit.

Catalysts for isomerization are similar to the platinum group metals on alumina support catalysts used for catalytic reforming. Because the volume of operating isomerization capacity is relatively small, catalyst consumption also is expected to be small, at about $10 million to $12 million in 1989. Restarting of shutdown isomerization units, conversion of other process units to isomerization, and new construction all are forecast to increase demand for isomerization catalysts. But because of the small base, even large increases will have little effect on the total refining catalyst market.

Under pressure to reduce emissions of hydrocarbons, carbon monoxide, and nitrogen oxides (NO_x) from automobile exhaust, demand for catalysts to reduce these emissions has increased rapidly. These catalysts are the largest segment of the catalyst business at about $650 million in the U.S. this year. Further reductions in emission levels, demands for longer life to the catalytic converters on autos, and extension of emission controls to large trucks and buses all will combine to increase demand for catalysts, almost entirely platinum group met-

Cost of catalysts for chemical manufacture rises slowly

$ Million	1982	1987	1992	2000
Polymerization	$208	$257	315	$430
Organic synthesis	70	84	100	130
Oxidation	80	95	110	135
Synthesis gas	43	54	63	80
Hydrogenation	28	34	40	50
Dehydrogenation	7	10	12	15
TOTAL	$436	$534	$640	$840

Millions of lb	1982	1987	1992	2000
Polymerization	46	55	65	85
Organic synthesis	74	86	97	115
Oxidation	10	13	15	17
Synthesis gas	14	17	20	25
Hydrogenation	8	10	12	15
Dehydrogenation	4	5	6	8
TOTAL	156	186	215	265
Catalyst cost, average ($ per lb)	$2.79	$2.87	$2.98	$3.17

Source: Freedonia Group

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Most major petrochemical processes depend on catalysts

Decade Beginning	Example of process or product[a]	Example of catalysts used
1900	Hydrogenation of fats	Ni
1910	Coal hydrogenation to liquid fuels	Fe
	Ammonia synthesis	Fe
1920	Methanol from synthesis gas	Zn, Cr oxides
	Hydrocarbons from synthesis gas	Fe/Co
1930	Fixed-bed catalytic cracking	Aluminosilicates
	Ethylene oxide	Ag
	Polyvinyl chloride	Peroxides
	Low-density polyethylene	Peroxides
1940	Catalytic reforming	Pt
	Synthetic rubbers—SBR	Li or peroxides
	Nitrile	Peroxides
	Butyl	Al
1950	High-density polyethylene	Ti or Cr
	Polypropylene	Ti
	Dehydrosulfurization	Co, Mo sulfides
	Terephthalic acid	Homogeneous Co/Mn
	Hydrocracking	Pt
1960	Maleic anhydride	V, P oxides
	Acrylonitriles	Bi, Mo oxides
	Improved catalytic cracking	Zeolites
	Adiponitrile from butadiene and HCN	Homogeneous Ni
	Phthalic anhydride from *o*-xylene	V, Ti oxides
1970	Methanol from synthesis gas	Cu, Zn, Al oxides
	Acetic acid via methanol and CO	Homogeneous Rh
	Linear low-density polyethylene	Ti, Cr
	α-Olefins via ethylene oligomerization	Homogeneous Ni, Mo/W
	Improved hydroformylation	Homogeneous Rh
1980	Methanol to gasoline	Zeolites
	Acetic anhydride from synthesis gas	Homogeneous Rh
	Methylmethacrylate from *tert*-butanol	Mo oxide
	Improved coal liquefaction	Co, Mo sulfides
	Improved coal gasification	Various metal salts

[a] C&EN selected examples. **Source:** G. Alex Mills, University of Delaware

als. If other industrialized countries follow the limits to auto emissions now in place in Japan and the U.S., and coming soon in Western Europe, the demand for emission control catalysts could jump again in the next decade.

The increased demand for emission reduction has led to greatly increased prices for these metals. Further increases are forecast. The Frost & Sullivan catalyst study for the U.S. puts the cost of a catalytic converter at about 2% of the total cost of a current, medium-priced automobile. If longer life and lower emissions are required, especially of nitrogen oxides, the converter could become 5% of the cost of a car. Much of the cost increase would result from increased use of rhodium in the catalyst, because this metal reduces NO_x better than other platinum group metals.

Further reducing industrial and power plant emissions also will increase catalyst demand. The value of the catalysts for industrial emission control, expected to be a small part of the total costs of emission control, could rise rapidly. The Freedonia Group estimates that industrial emission controls will require catalysts worth $85 million by 1992, up from $25 million in 1987, and nearly quadrupling to $330 million by 2000.

Yet another area of catalysts are the biocatalysts, largely enzymes. A few industrial processes, such as sugar transformations, semisynthesis of antibiotics, and transformations of steroids, are catalyzed by enzymes. The value of enzymes used as catalysts is estimated at $100 million to $150 million this year. Several barriers to their use include high cost; liability to heat, variations in pH, and solvents; and often a narrow selectivity, according to Perry A. Frey of the Institute of Enzyme Research at the University of Wisconsin.

Use of genetic engineering to aid enyzme production and to increase thermal stabilities, as well as to design specificities, remains in its in-

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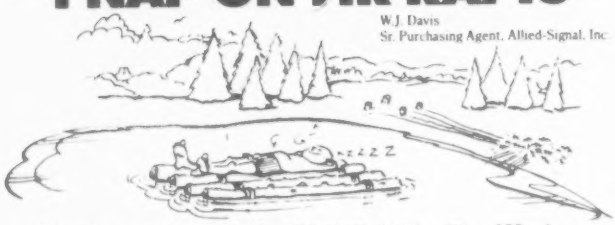

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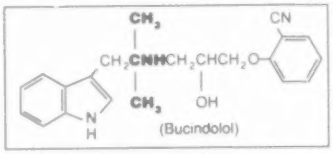

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fancy, according to Frey. Some early results of work in this field suggest that enzymes could become increasingly versatile catalysts for certain applications. Large-scale use will come, but it will take time.

Improvements in catalysts and catalytic processes to produce fuels and chemicals hold down growth in both volume and value of catalysts. In the area of chemicals, James A. Cusumano, chairman of Catalytica, a firm that specializes in development of catalysts and processes in Mountain View, Calif., points out numerous examples of changes in routes to well-known products. For example, improved catalysts are leading to more efficient butane oxidation for making maleic anhydride, including use of fluidized-bed technology. Other possibilities include direct oxidation of benzene to phenol (thereby bypassing cumene), carboxylation to make methyl methacrylate (avoiding use of cyanohydrin), and conversion of maleic anhydride to make 1,4-butanediol (avoiding use of acetylene).

In the petroleum refining processes, several developments will be coming, Cusumano says. One will be catalysts that improve isomerization by operating at lower temperatures. In naphtha reforming, new catalysts to partially replace platinum group metals will be developed using designs to adjust the acidity on the surface (either inside or outside the pores).

Emission control catalysts also are being improved. Catalysts currently are being developed to aid processes that handle very low concentrations of organic compounds and oxides of sulfur and nitrogen. Other catalytic processes also are being developed to efficiently make fuel components, such as methanol and other oxygenates that reduce exhaust pollutants.

Further development of catalysts for these and other uses will likely keep the catalyst business on a long-term growth curve. As long as chemical reactions are used in processes to make products or handle wastes, catalysts will be crucial to economic success of the processes. The 0.1 to 0.3% of product costs spent on catalysts for processing has proved to be an excellent value. □